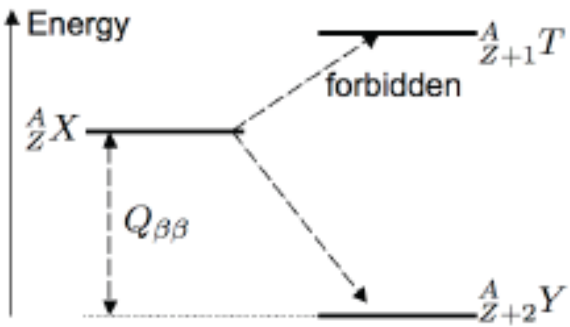
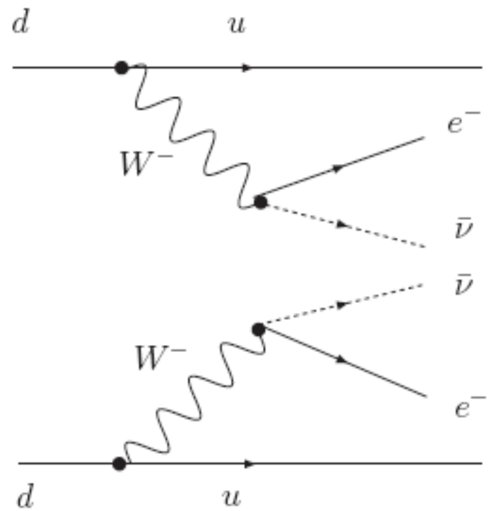
CUORE: Search for Neutrinoless Double Beta Decay in ^{130}Te

October 26, 2016

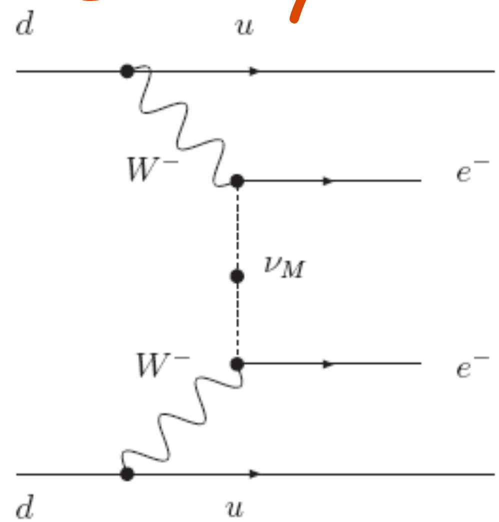
Yury Kolomensky
LBNL

Neutrinoless Double-Beta Decay





SM 2νββ decay $\tau \geq 10^{19}$ y



0νββ $\tau \geq 10^{25}$ y

- Observation of 0νββ would mean
  - Lepton number violation
  - Neutrinos are Majorana particles
  - Rate measures (effective) electron neutrino mass

$$\boxed{m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|}$$

Cryogenic Underground Observatory for Rare Events

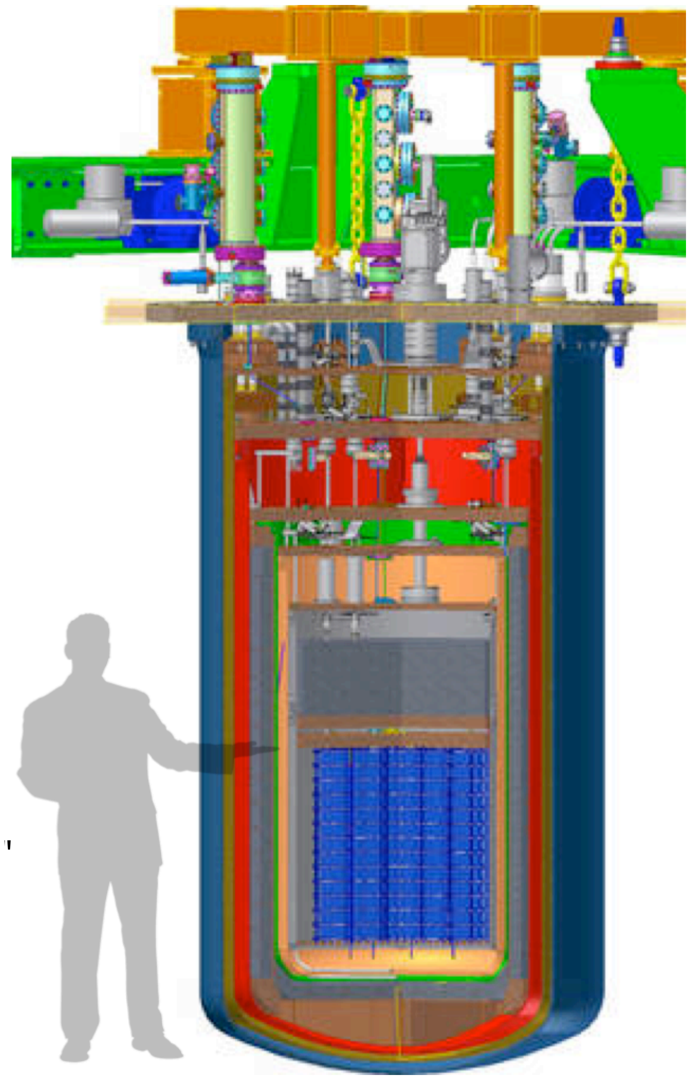
CUORE: Cryogenic Underground Observatory for Rare Events

Array of 988 TeO_2 crystals

- **19** towers suspended in a cylindrical structure
- **13** levels, **4** crystals each
- 5x5x5 cm^3 (750g each)
- ^{130}Te: 33.8% natural isotope abundance

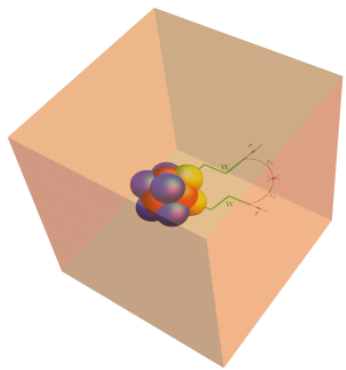
750 kg TeO_2 => 200 kg ^{130}Te

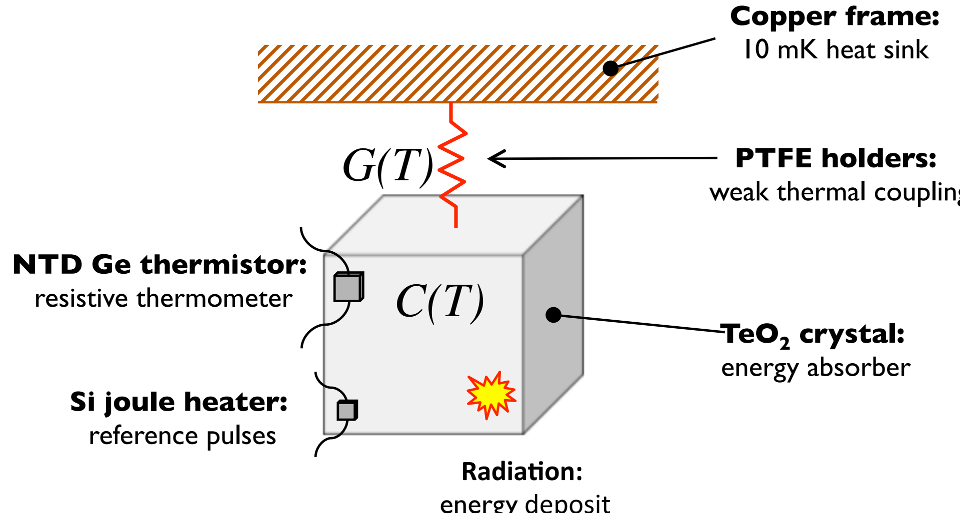
- New pulse tube refrigerator and cryostat
- Radio-purity techniques and high resolution achieve low backgrounds
- Joint venture between Italy (INFN) and US (DOE, NSF)
- Under construction (expected start of operations in late 2016)
- Expect energy resolution of 5 keV FWHM and background of ~0.01 counts/(kg*keV*year) in ROI

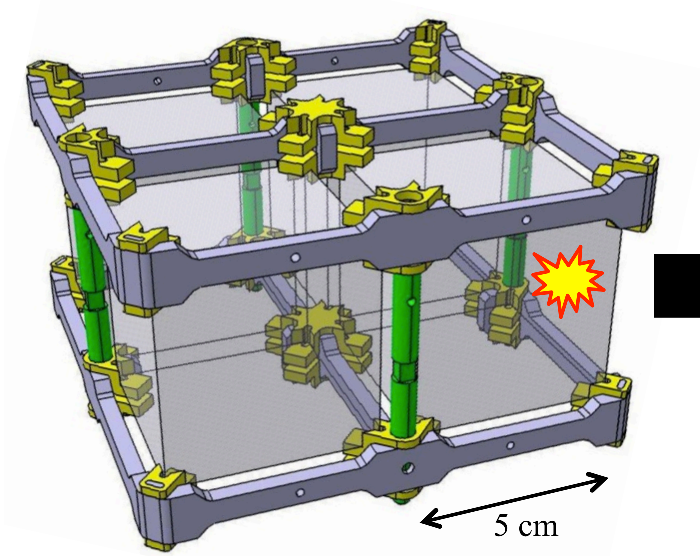


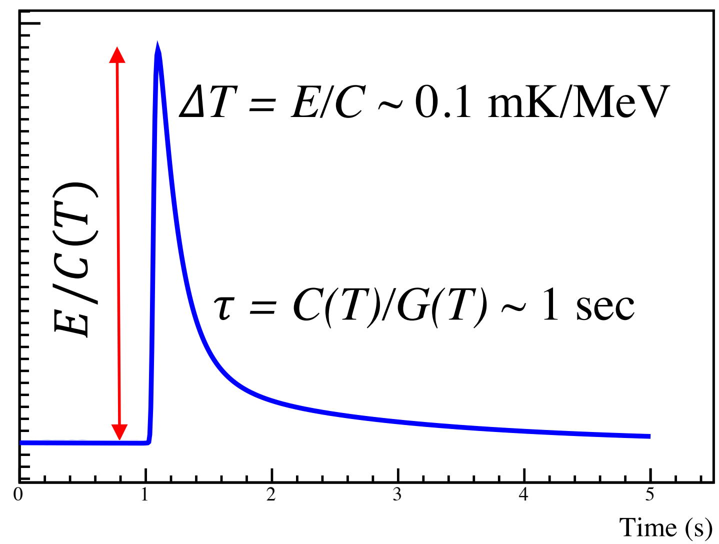
Cryogenic Bolometers

Source = Detector



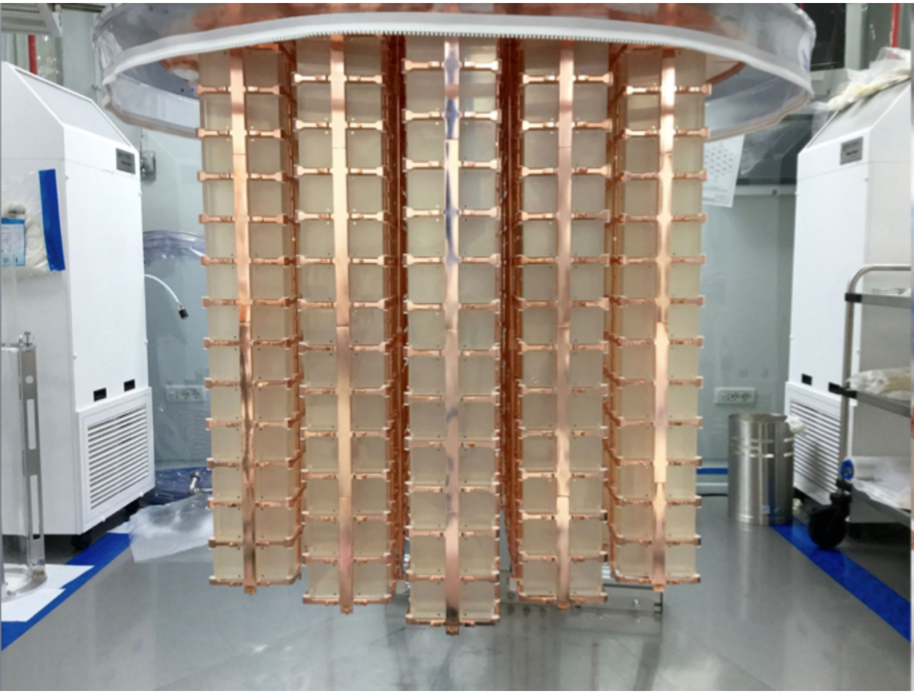


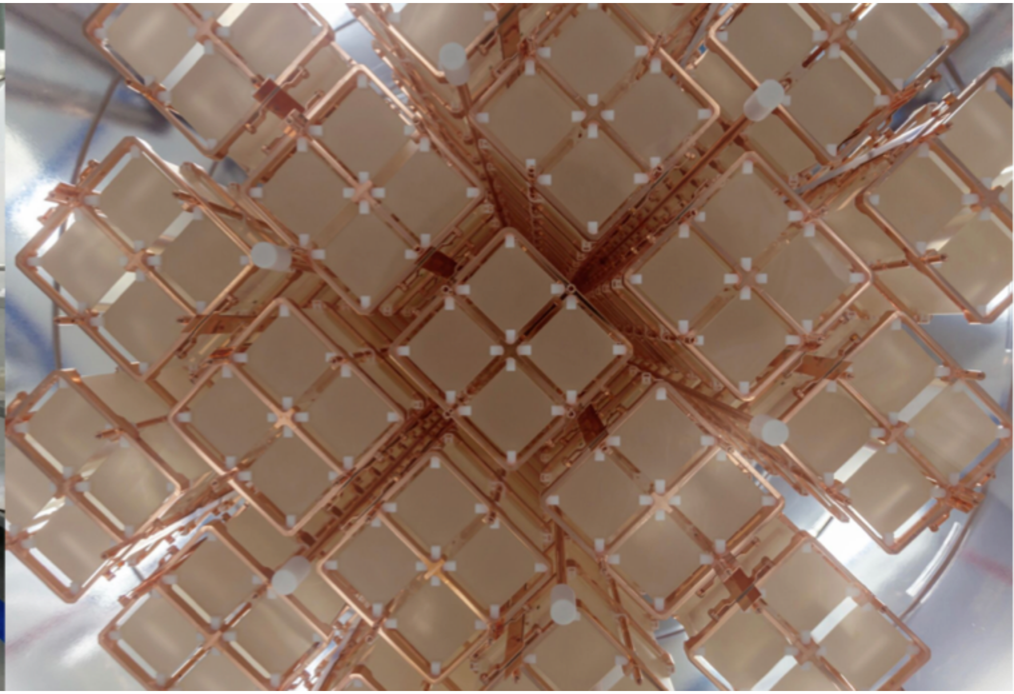




Ultra-cold TeO_2 crystals function as very sensitive calorimeters

CUORE Detector



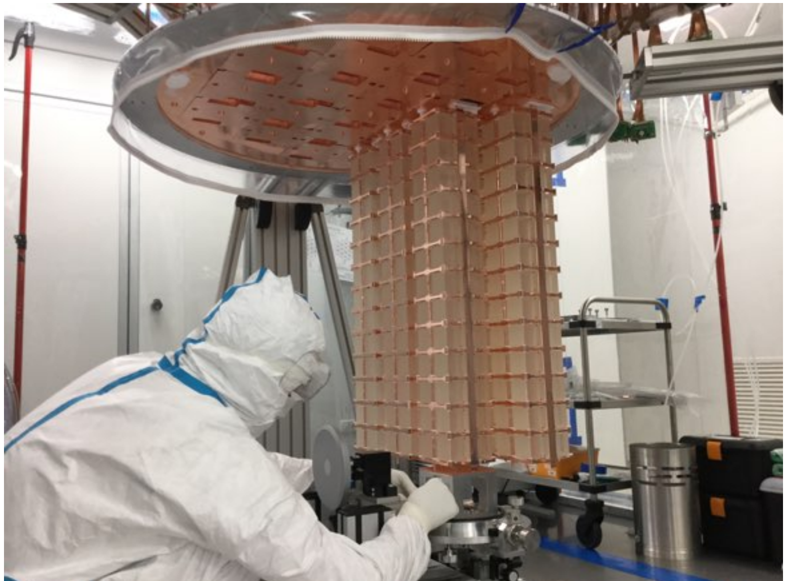


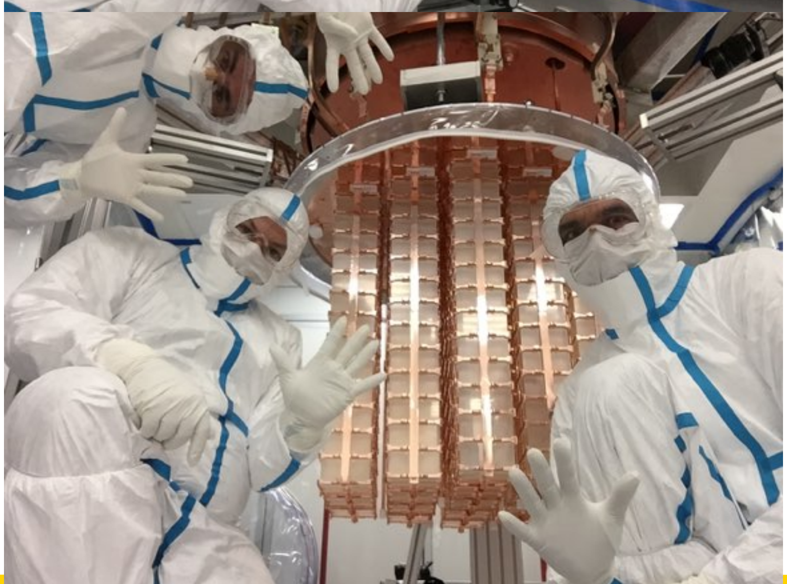
August 2016: all towers installed in cryostat

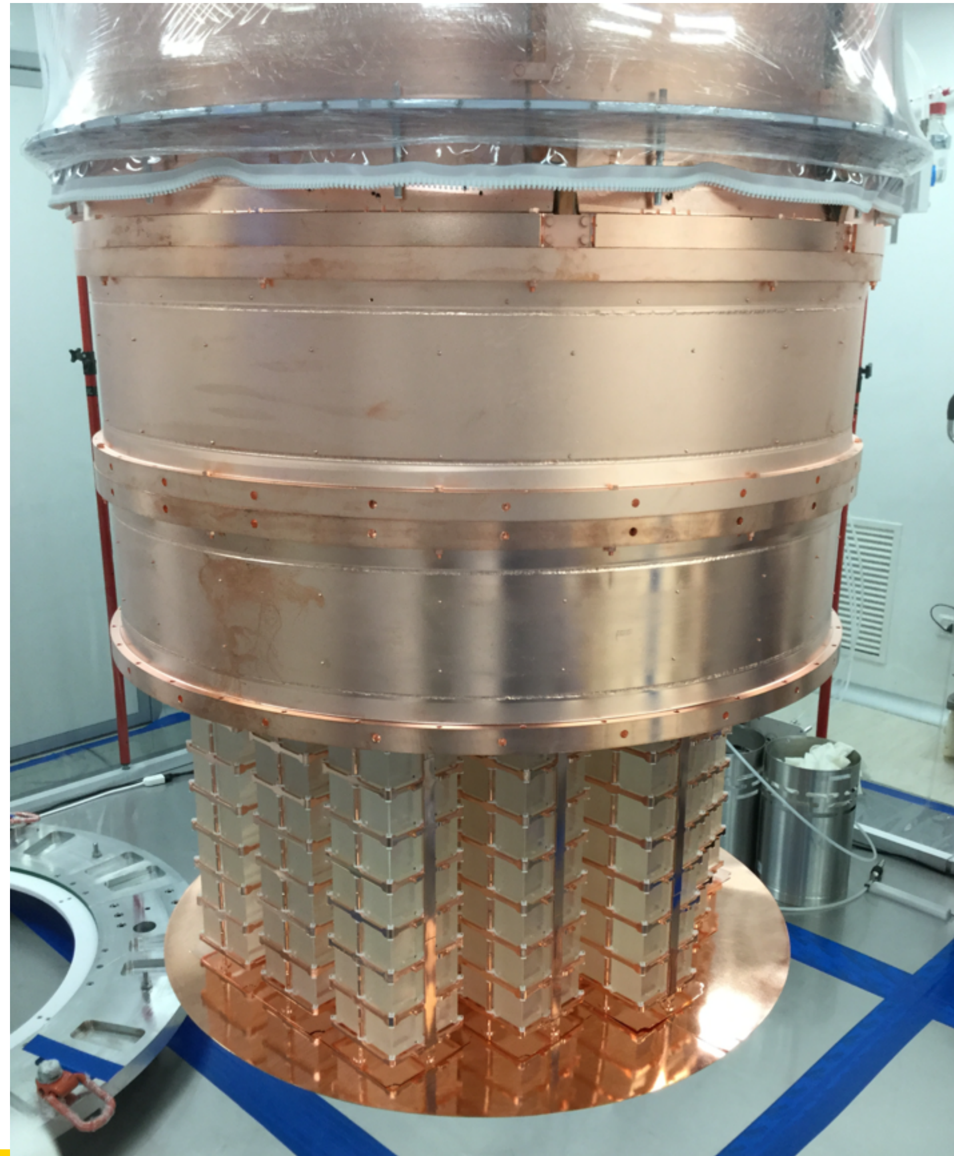
980/988 channels checked out and fully operational (2 more may be operational)

First cooldown expected in November

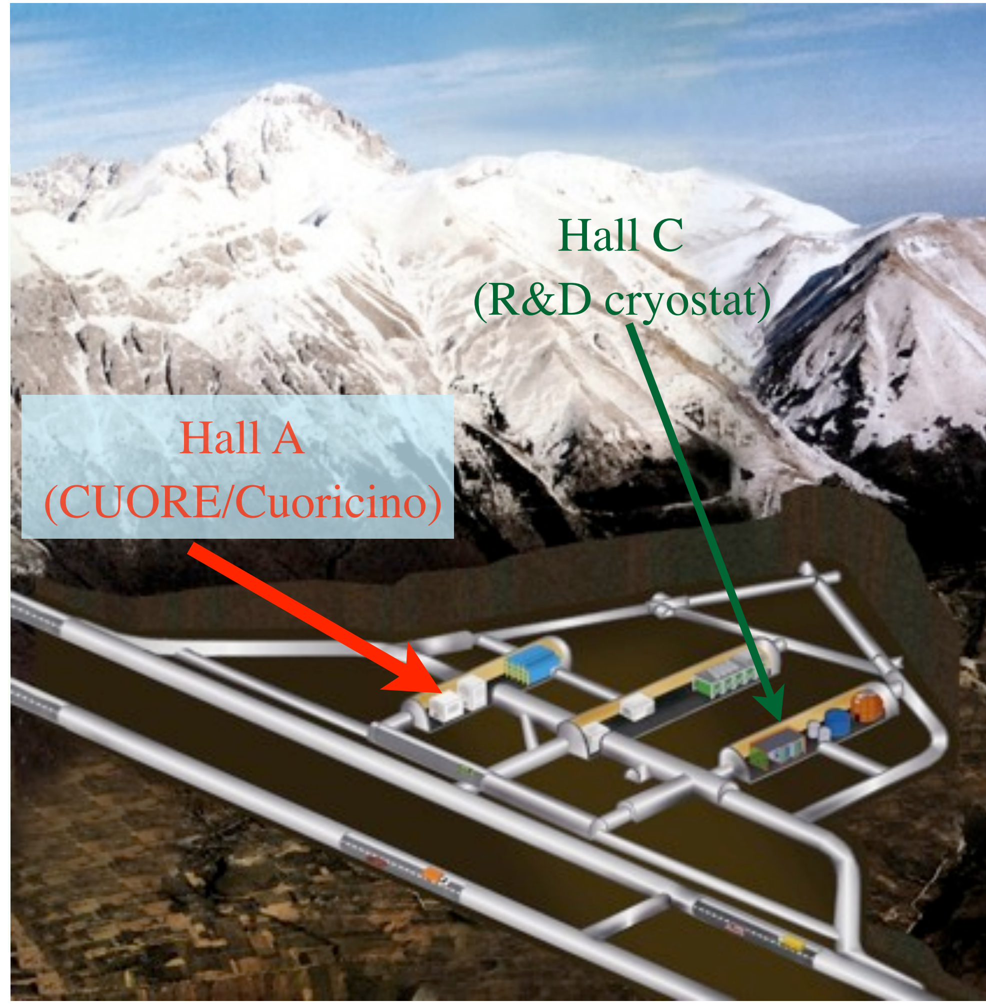
Detector Installation





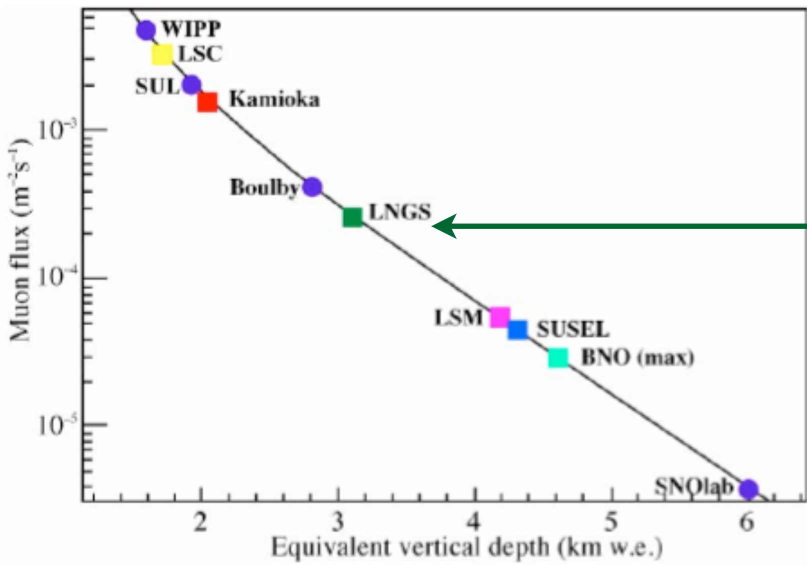


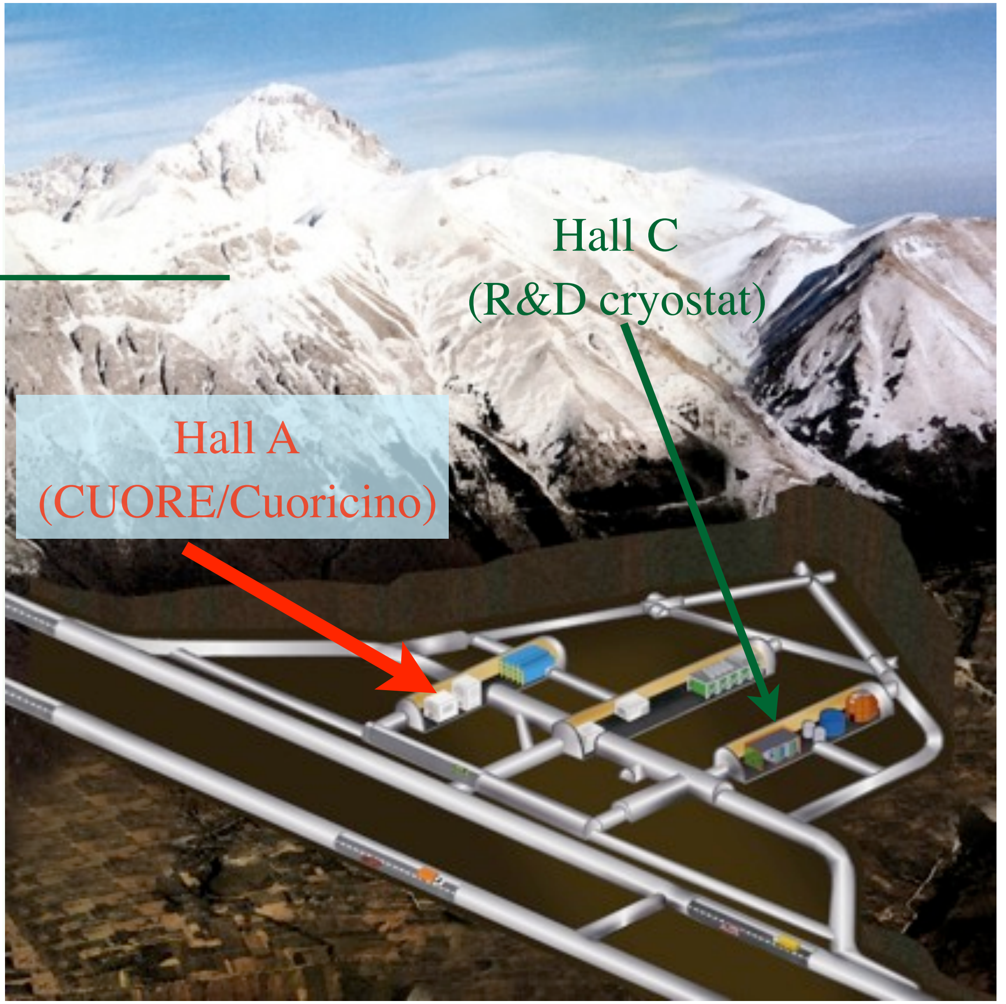
Gran Sasso Laboratory



CUORE under construction in Hall A

Gran Sasso Laboratory





Shielding: ~3650 m.w.e.
Muons: ~2 x 10^{-8}/cm^2-s
Thermal neutrons: ~1 x 10^{-6}/cm^2-s
Epithermal neutrons: ~2 x 10^{-6}/cm^2-s
> 2.5 MeV Neutrons: 2 x 10^{-7}/cm^2-s

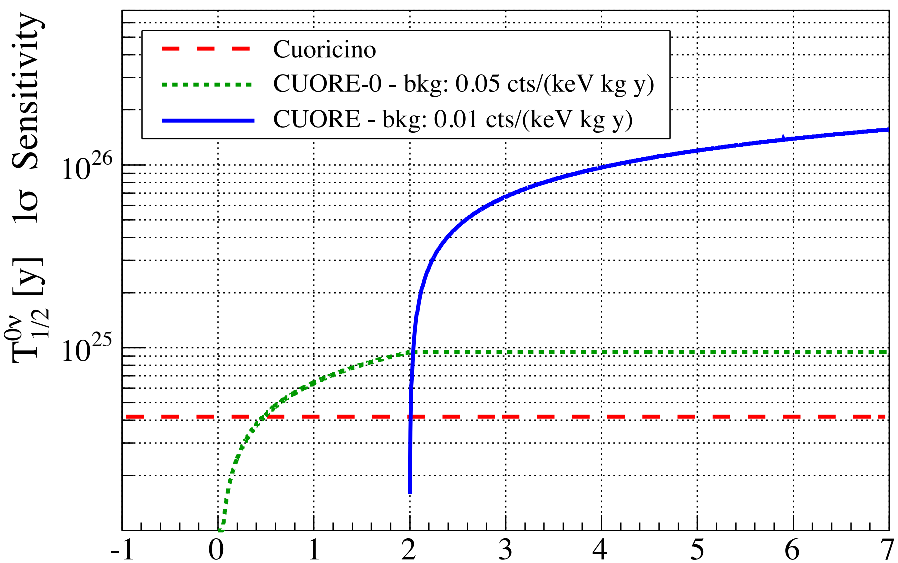
CUORE under construction in Hall A

CUORE: Ultimate Performance

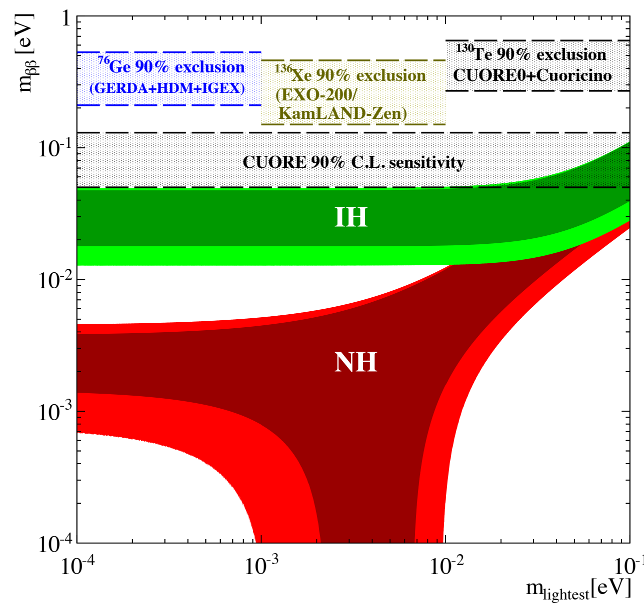
Parameter	Performance
Average energy resolution for all crystals	<5 keV FWHM
Background index in the DBD region of interest (2528 keV +/- 10 keV)	<0.01 counts/(kg*keV*year)
Selection Efficiency > 85%	> 85 %

$T_{1/2}$ sensitivity 0.95×10^{26} years @ 90% C.L. (5 years)

$m_{\beta\beta}$ sensitivity 50-130 meV @ 90% C.L. (5 years)



Start by end of 2016 ! Live time [y]



US CUORE Collaboration

- Funded by DOE-NP (LBNL, LLNL, UCB, Yale), NSF-NP (CalPoly, UCB, UCLA, USC), and institutional funds (MIT, VT, Yale)
- Separate funding for project and research/operations
- Leadership structure:
  - US-CUORE Spokesperson: YGK
  - US Representatives to Executive Board
    - F. Avignone, K. Heeger, YGK, S. Zimmermann
  - Each group represented in CUORE Council (BKF, YGK)
  - US representatives in all scientific boards
    - Physics Board (L. Winslow), Speakers' Board (T. Gutierrez, B. Fujikawa), Publication Board (J. Ouellet), Vetting Board (J. Cushman), Council Chair (R. Maruyama)

CUORE LBNL/UC Berkeley Group

Lawrence Berkeley National Laboratory and UC Berkeley

J. Beeman, J. Benato, D. Biare, J. Camilleri, L. DiPaolo, A. Drobizhev, S.J. Freedman†, B.K. Fujikawa, E.E. Haller, R. Hennings-Yeomans, R.W. Kadel, Yu.G. Kolomensky, Y. Mei, S. Morgan, B. Schmidt, B. Sheff, V. Singh, T. Sipla, A.R. Smith, M. Turqueti, S.L. Wagaarachchi, J. Wallig, B. Welliver, S. Yellamilli, S. Zimmermann

†deceased

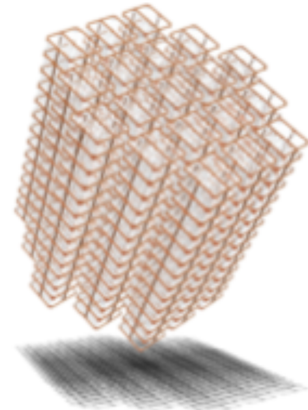
graduate student (x)	postdoc (x)	faculty (2)
undergraduate student (x)	technical staff (x)	staff (10)
Total: xx	Authors: xx	

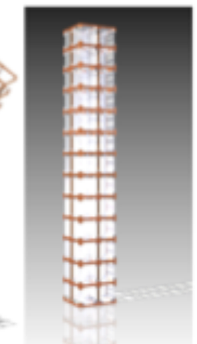
NSD Personnel:

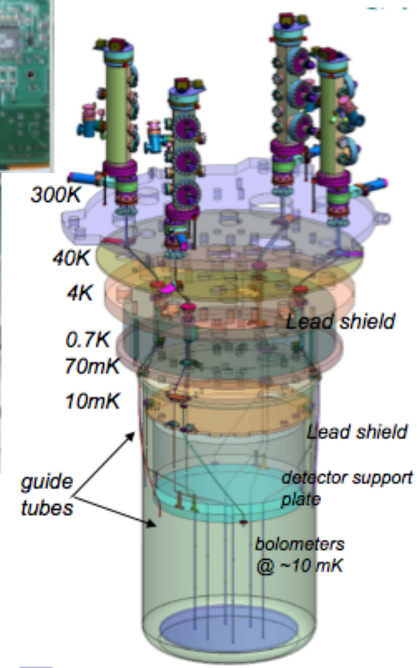
- Group leader, staff scientist: Brian Fujikawa
- Senior Faculty Scientist: Yury Kolomensky
- Staff: Yuan Mei
- Postdocs: Benjamin Schmidt, Bradley Welliver

US Contributions to CUORE

- Project management: LBNL
- Detector
  - 503 TeO_2 crystals procured @ SICCAS (LLNL, LBNL)
  - ~1500 NTD thermistors (LBNL, UCB)
  - Detector assembly, integration, and commissioning (common): leading role by UCB/LBNL
- Electronics (NSF contribution: USC, UCLA)
- Calibration system (UWisc/Yale)
- Anti-radon system (LBNL)
- DAQ and analysis tools, farm (UCB, LBNL)
- Data analysis (all)
- Slow monitoring (MIT)







LBNL: Installation and Commissioning

- Involved in critical tasks:
  - Cryogenics
    - ☞ Cryogenic support, temperature stabilization
  - Detector installation
    - ☞ Tower support team, radon abatement system, clean room
  - Online data processing
    - ☞ Online data processing, slow controls
  - Early data analysis

Major Milestones

- Cooldown start: Nov 2016
- Commissioning: Winter 2016-2017
- Early data: Spring 2017
- First results: late 2017
  - First CUORE theses 2017-2018
- Full dataset: ~5 years of livetime, ~6 years of operations

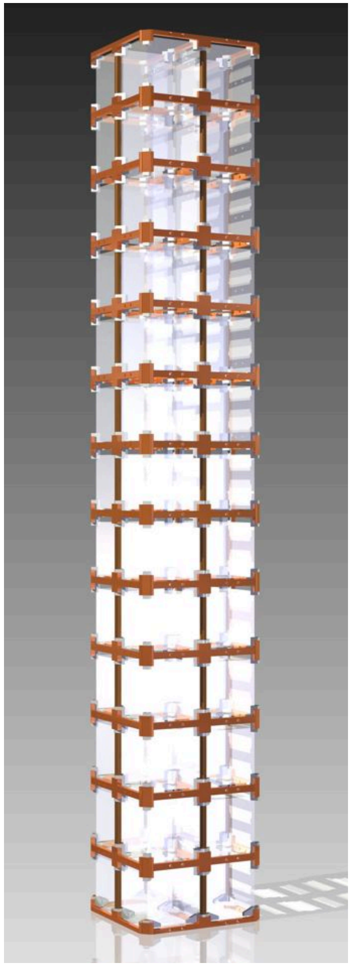
Expect ~1 FTE onsite from LBNL planned next year

Requires substantial travel support, especially during installation and commissioning

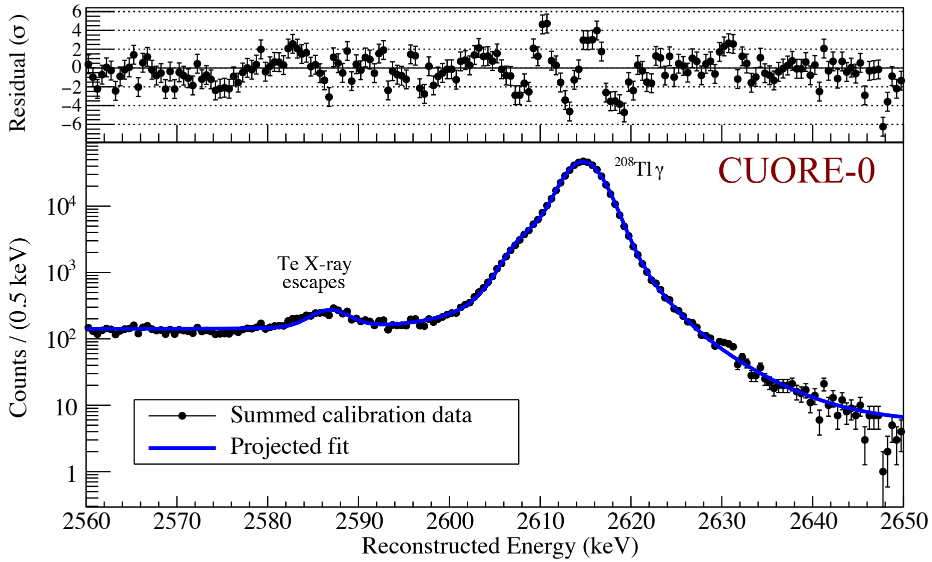
Science Highlights: CUORE-0

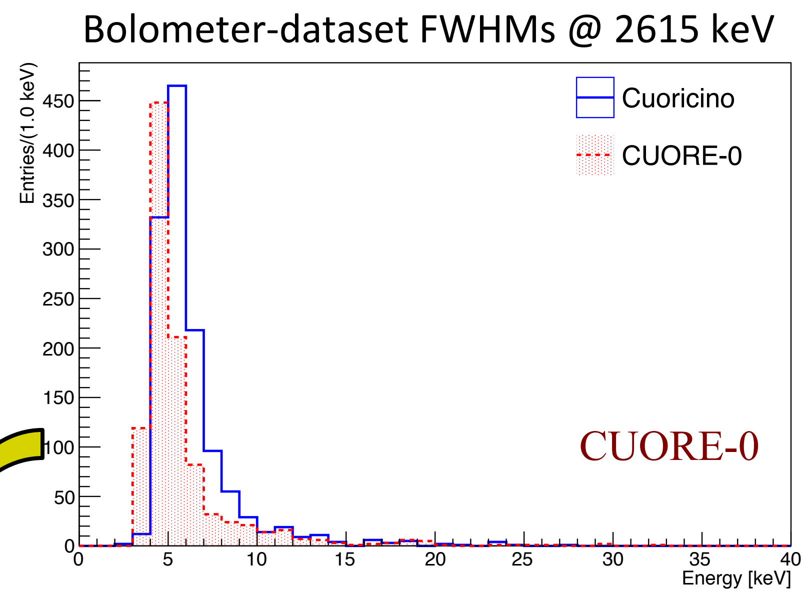
CUORE-0

- First tower from the CUORE detector assembly line
- 52 TeO_2 crystals, total mass = 39 kg TeO_2 = 10.9 kg ^{130}Te
- Purpose:
  1. Commission assembly line
  2. Run as standalone experiment while CUORE is being constructed, with aim of surpassing Cuoricino
  3. Validate CUORE detector design
  4. Provide test bed for developing DAQ & analysis framework for CUORE
- Operating in former Cuoricino cryostat since March 2013



Energy Resolution



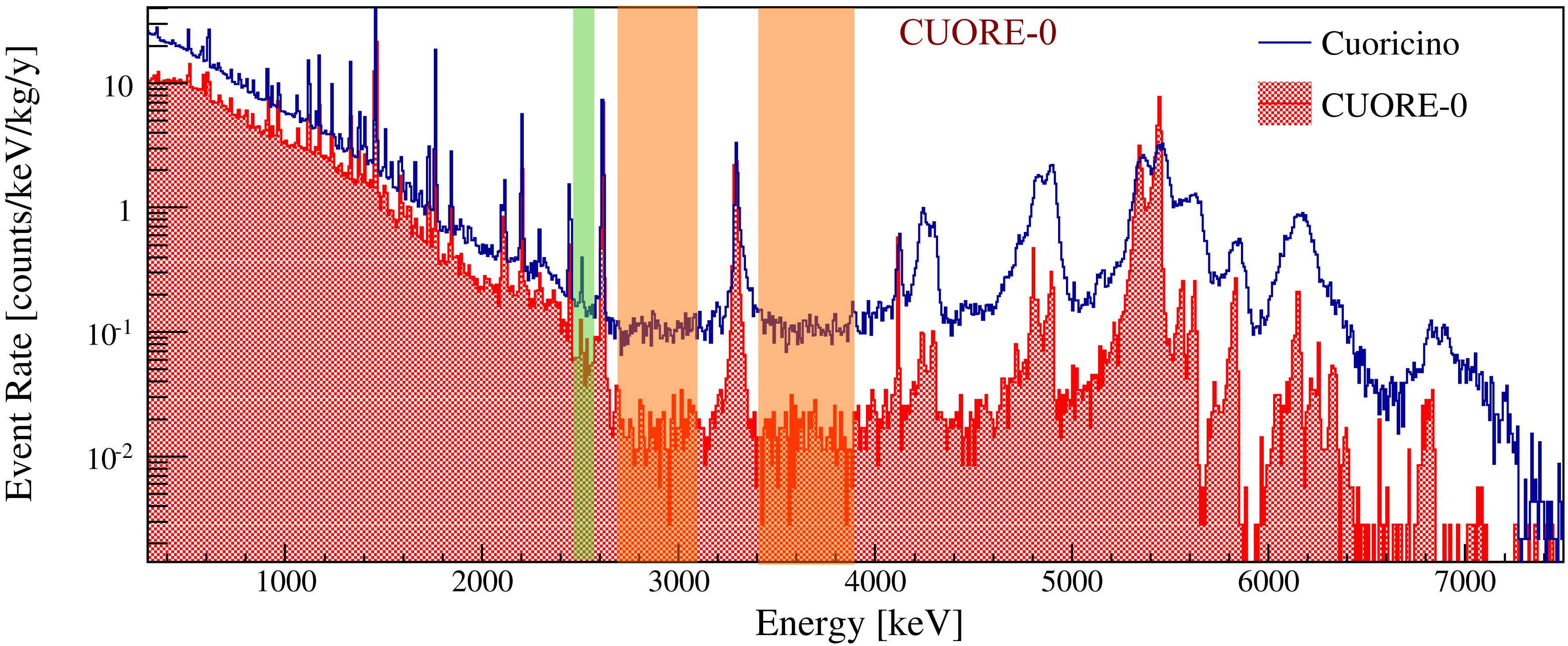


Weight FWHMs by corresponding physics exposure

	FWHM harmonic mean (keV)	FWHM dist RMS (keV)
Cuoricino	5.8	2.1
CUORE-0	4.9	2.9

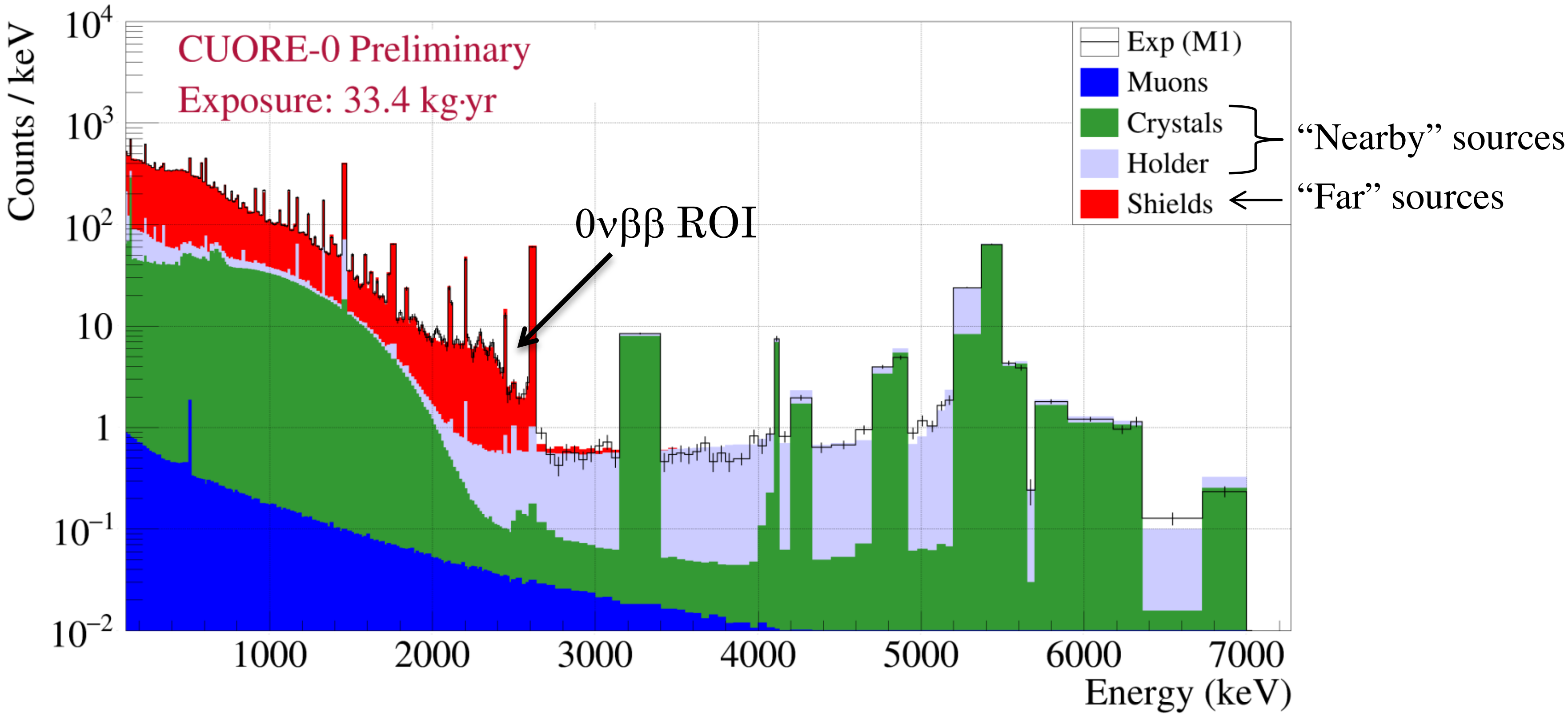
- We evaluate the energy resolution for each bolometer and dataset by fitting the ^{208}Tl photopeak in the calibration data
- We achieved the 5 keV resolution goal of CUORE!

Backgrounds



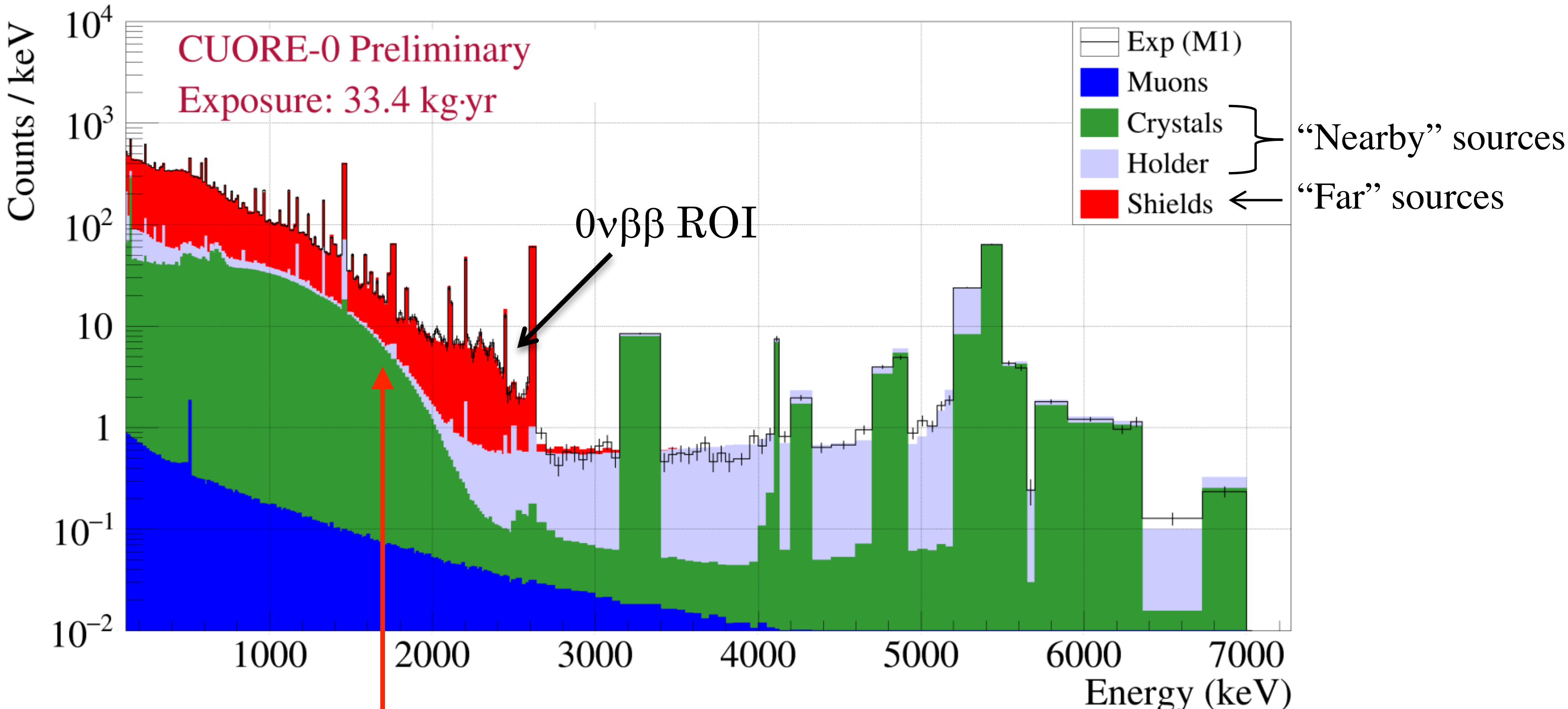
Experiment	Background rate (counts/keV/kg/y)	
	$0\nu\beta\beta$ decay region	Alpha region (excl. peak)
Cuoricino	0.169 ± 0.006	0.110 ± 0.001
CUORE-0	0.058 ± 0.004	0.016 ± 0.001

CUORE-0 Background Analysis



arXiv:1609.01666

CUORE-0 Background Analysis



$$\text{CUORE-0: } T^{2\nu}_{1/2} = [8.2 \pm 0.2\ (\text{stat.}) \pm 0.6\ (\text{syst.})] \times 10^{20}\ \text{y}$$

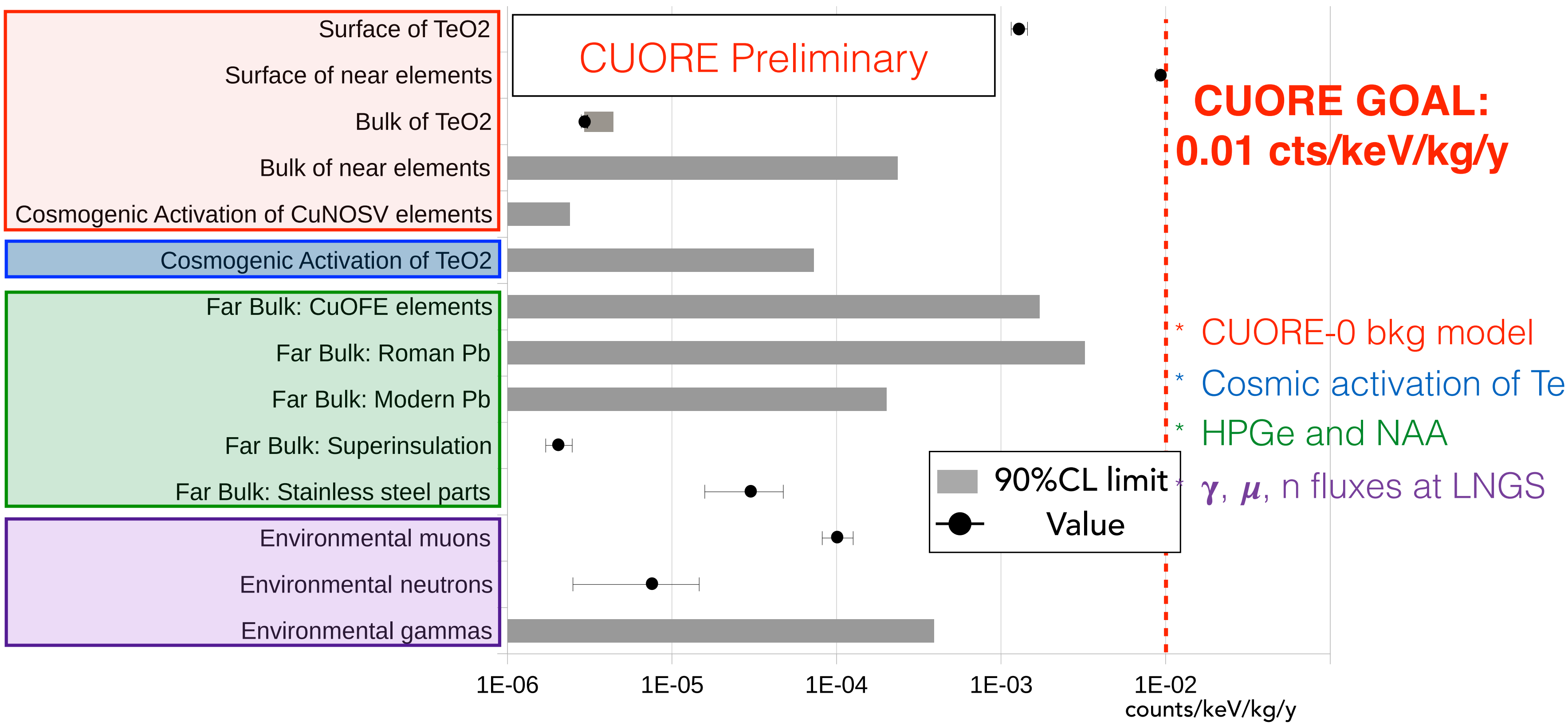
arXiv:1609.01666

$$\text{NEMO: } T^{2\nu}_{1/2} = [7.0 \pm 0.9\ (\text{stat.}) \pm 1.1\ (\text{syst.})] \times 10^{20}\ \text{y}$$

$$\text{MiDBD: } T^{2\nu}_{1/2} = [6.1 \pm 1.4\ (\text{stat.})\ {}^{+2.9}_{-3.5}\ (\text{syst.})] \times 10^{20}\ \text{y}$$

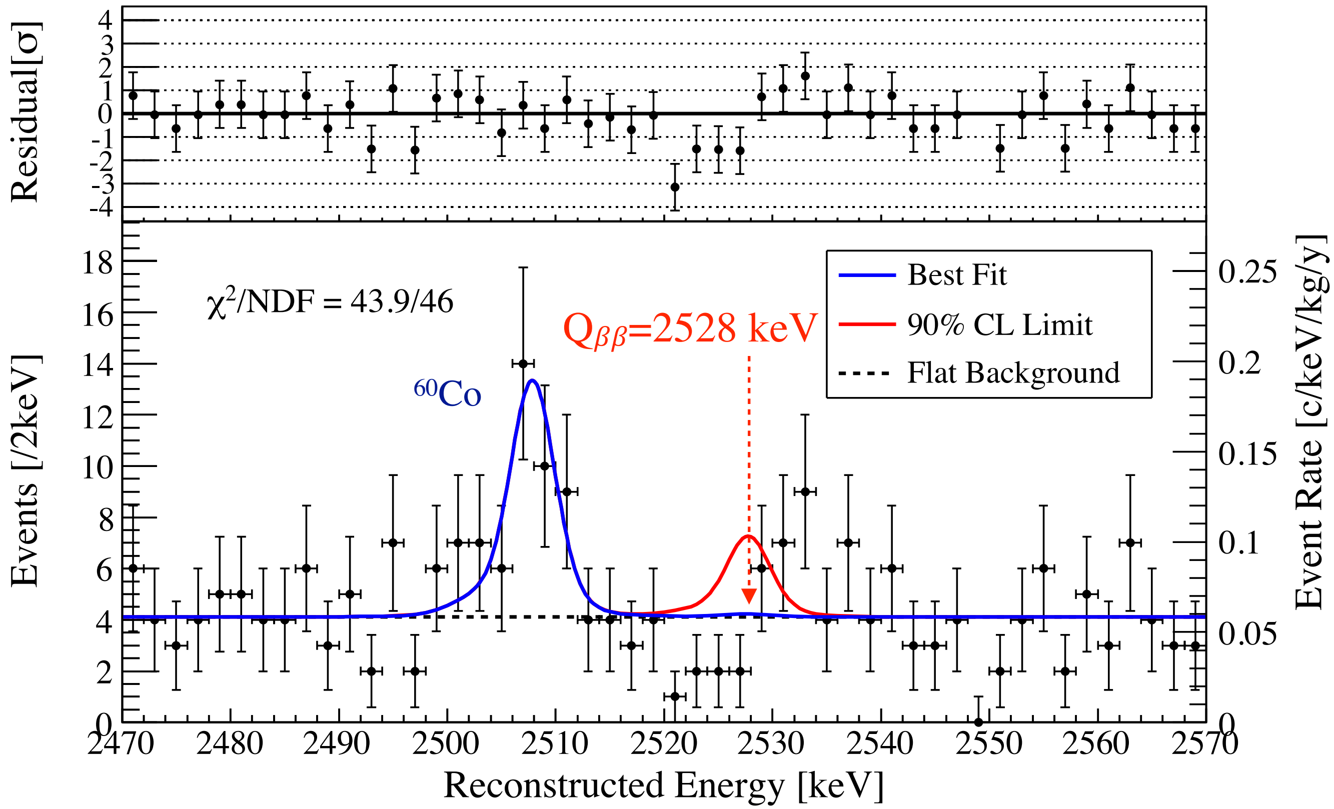
CUORE

CUORE Background Expectation



CUORE-0 results confirm CUORE background expectations and ultimate sensitivity

CUORE-0 $0\nu\beta\beta$ Fit

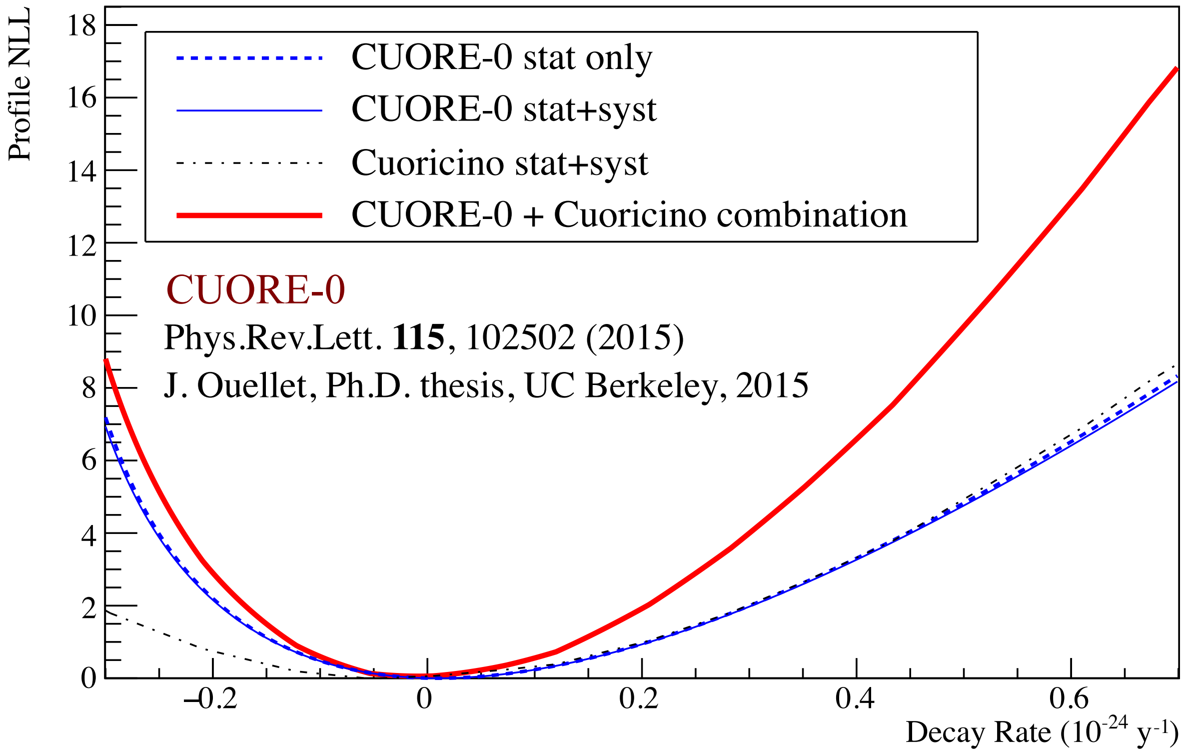


After accounting for systematic uncertainties we report the Bayesian limits:

$$\Gamma^{0\nu\beta\beta}(^{130}\mathrm{Te}) < 0.25 \times 10^{-24}\ \mathrm{yr}^{-1}\ (90\%\ \mathrm{C.L.,\ stat.+syst.})$$

$$T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) > 2.7 \times 10^{24}\ \mathrm{yr}\ (90\%\ \mathrm{C.L.,\ stat.\ +\ syst.})$$

Combination with Cuoricino



Combining the CUORE-0 result with the Cuoricino result from 19.75 kg-yr of ^{130}Te exposure yields the Bayesian lower limit:

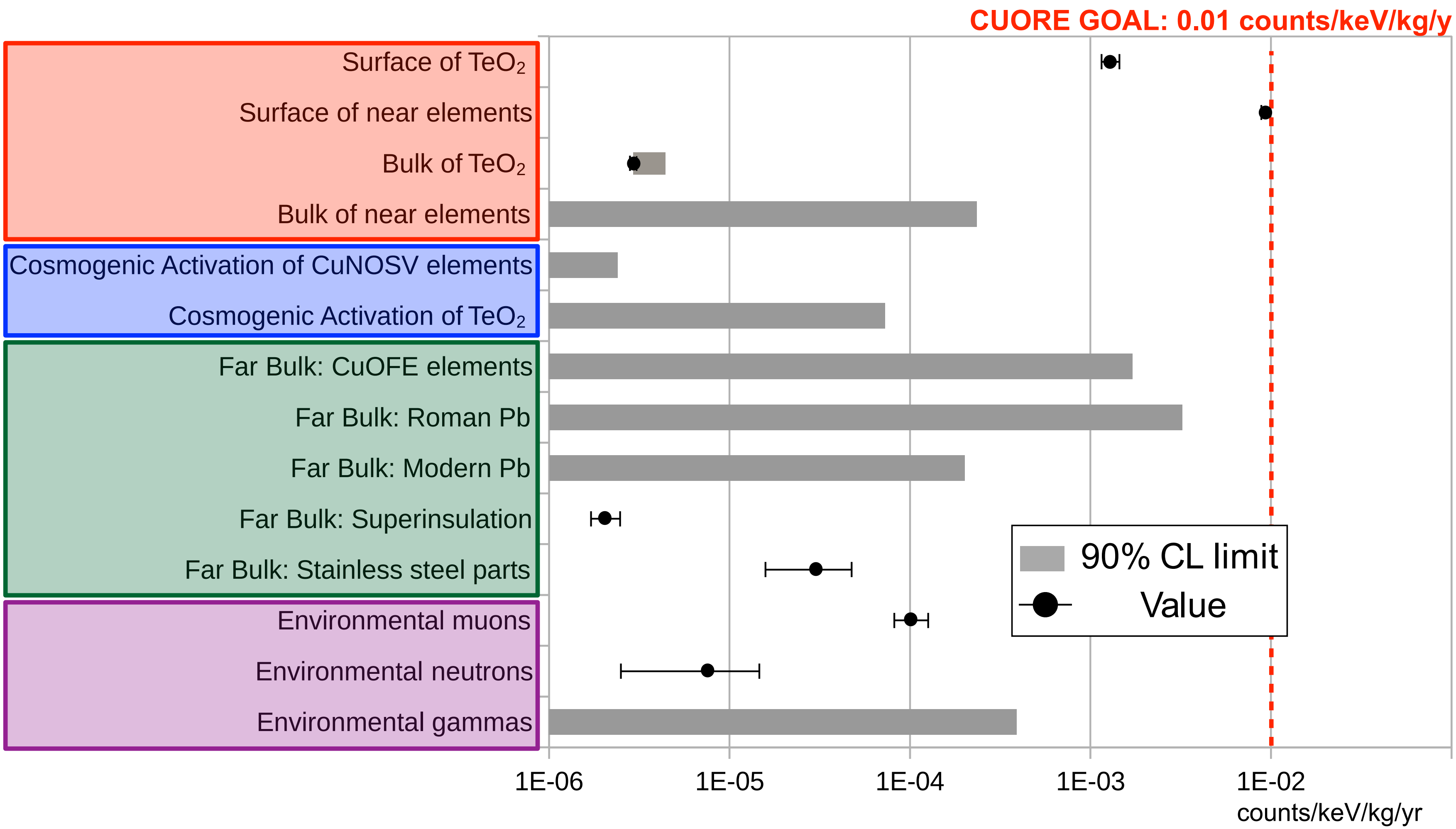
$$T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) > \ 4.0 \times 10^{24}\ \mathrm{yr}\ \ (90\%\ \mathrm{C.L.})$$

Jonathan Ouellet, 2017 Dissertation Award in Nuclear Physics

"For his outstanding contributions to the search for neutrinoless double beta decay of ^{130}Te, and setting a new limit on its decay half-life, at the Cryogenic Underground Observatory for Rare Events in Gran Sasso, Italy."

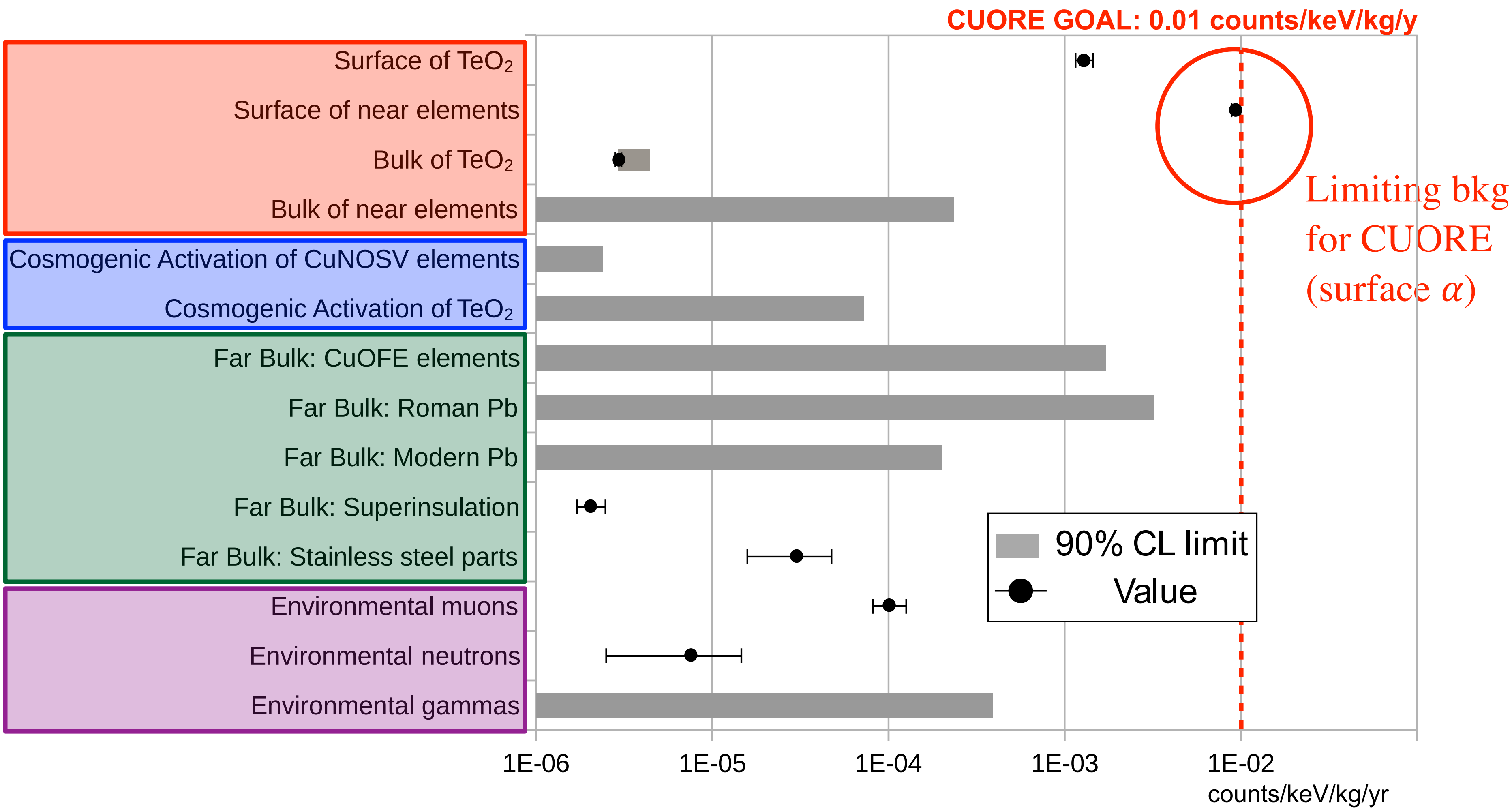
Beyond CUORE: CUPID

CUORE Background Model



K. Alfonso et al., "Projected background budget of the CUORE experiment", in preparation

CUORE Background Model

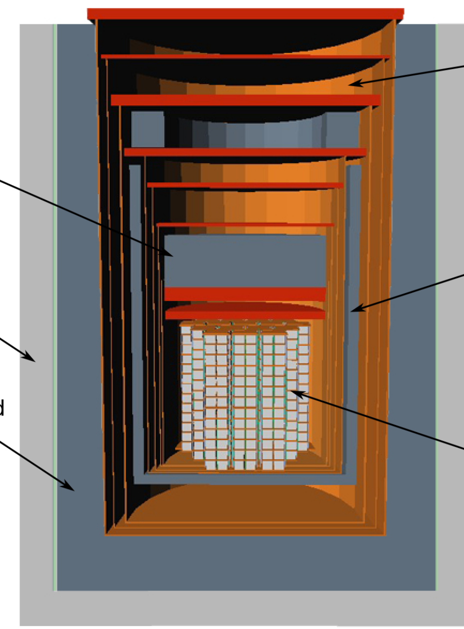


K. Alfonso et al., "Projected background budget of the CUORE experiment", in preparation

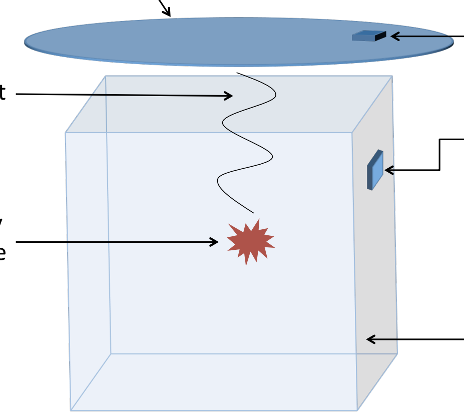
CUORE Upgrade with Particle ID (CUPID)

R. Artusa et al., Eur.Phys.J. **C74**, 3096 (2014)
White papers: arXiv:1504.03599 & arXiv:1504.03612

- Next-generation bolometric tonne-scale experiment
- Based on the CUORE design, CUORE cryogenics
- 988 enriched (90%) crystals, PID with light detection
  - 4 crystals considered:
    - ☞ TeO_2 : phonons + Cherenkov detector
    - ☞ Options: ZnSe, $ZnMoO_4$, $CdWO_4$ (phonons+scintillation)

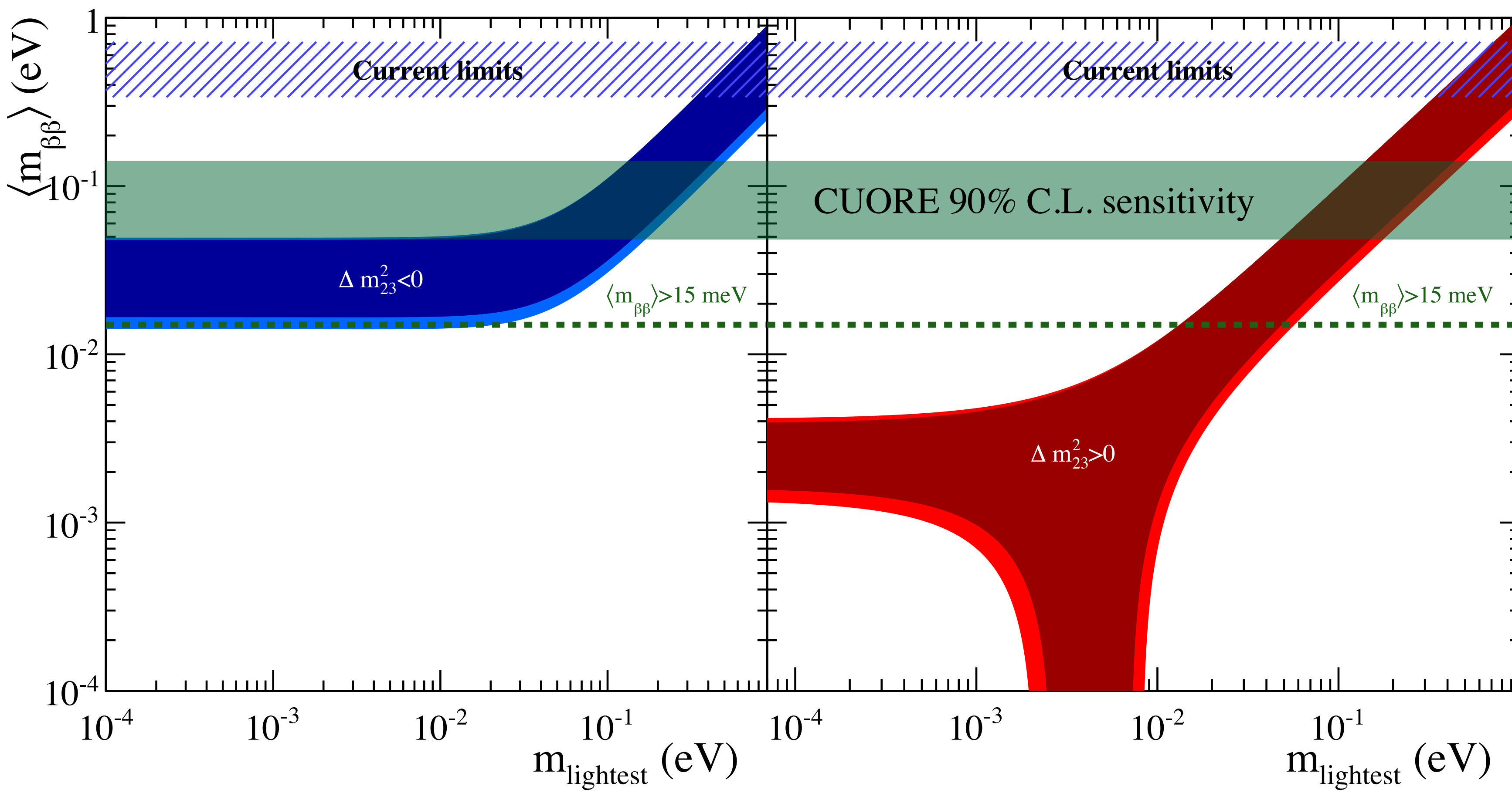


- Sensitivity to entire IH region
  - ☞ CUORE geometry and background model
  - ☞ Challenge: nearly zero background measurement background goal < 0.1 events / (ROI ton*year)
  - ☞ 99.9% α rejection @ >90% signal efficiency
  - ☞ 5 keV FWHM resolution
  - ☞ Half-life sensitivity (2-5)×10^{27} years in 10 years (3σ)
  - ☞ $m_{\beta\beta}$ sensitivity 6-20 meV (3σ)



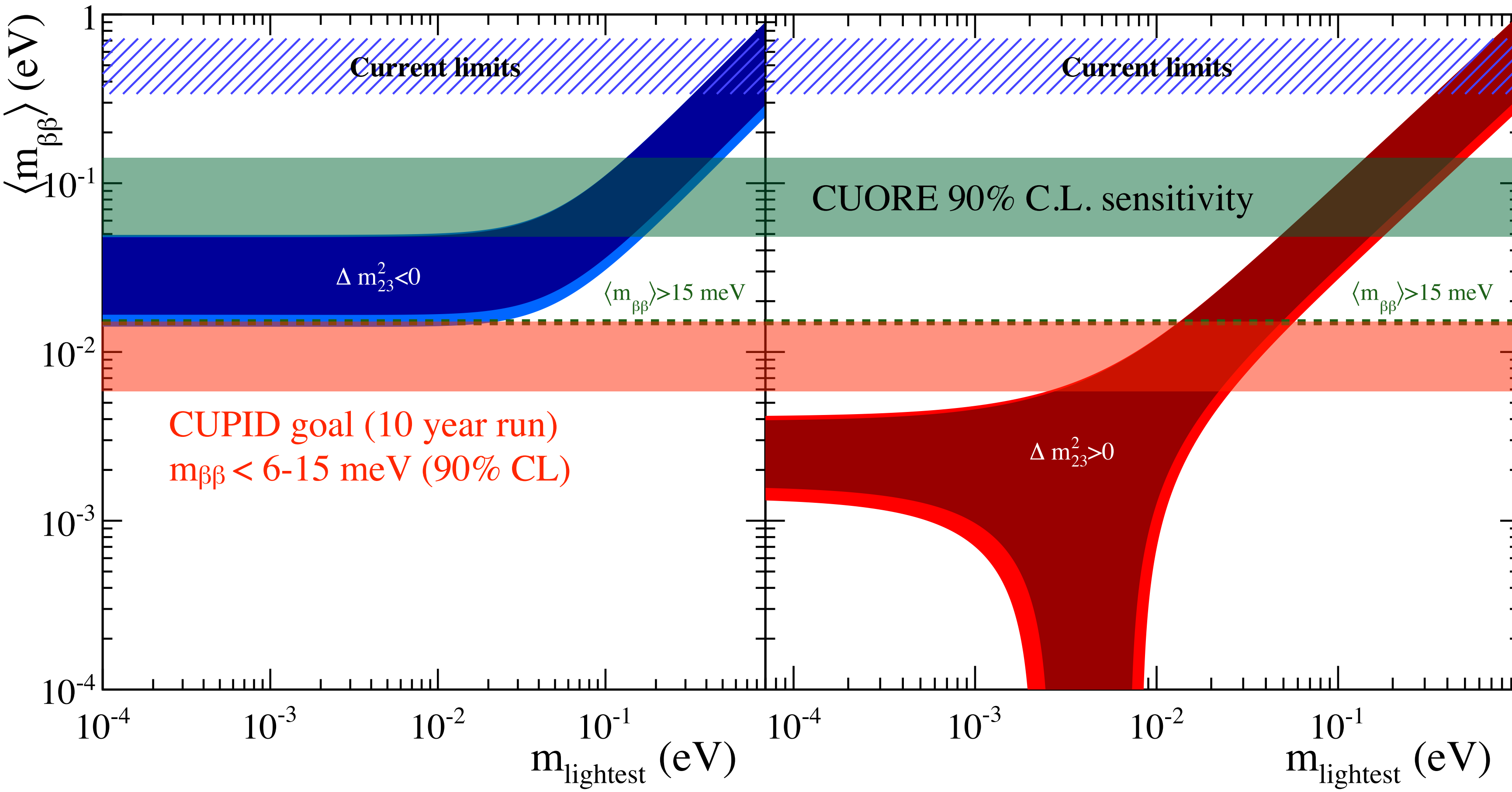
Subject of focused R&D effort in next 2-3 years

CUPID Sensitivity



$$m_{\beta\beta} = \left|\sum_i m_i \cdot U_{ie}^2\right|$$

CUPID Sensitivity



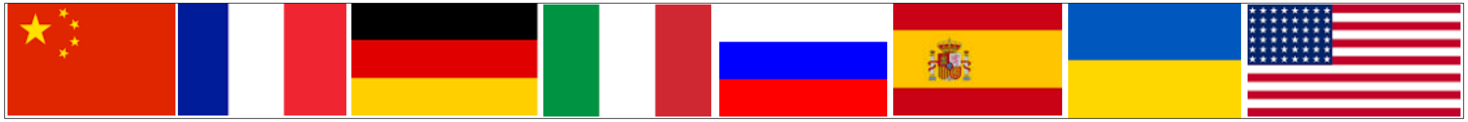
$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

Outlook

- CUORE is a major DBD experiment, with a potential to be the leader in this field through the end of the decade
- LBNL is playing a leading role in this and future project

Backup

CUPID Interest Group



High Energy Physics Division, Argonne National Laboratory, Argonne, IL, USA
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Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
Department of Nuclear Engineering, University of California, Berkeley, CA, USA
Department of Physics, University of California, Berkeley, USA
Università di Bologna and INFN Bologna, Bologna, Italy
Massachusetts Institute of Technology, Cambridge, MA, USA
Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA
Technische Universität München, Physik-Department E15, Garching, Germany
Dipartimento di Fisica, Università di Genova and INFN - Sezione di Genova, Genova, Italy
Institute for Nuclear Research, Kyiv, Ukraine
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Institut de Physique Nuclèaire de Lyon, Universitè Claude Bernard, Lyon 1, Villeurbanne, France
Wright Laboratory, Department of Physics, Yale University, New Haven, CT, USA
Laboratorio de Fisica Nuclear y Astropartculas, Universidad de Zaragoza, Zaragoza, Spain

α/β Discrimination

- Active background suppression with dual bolometric readout (heat+light)
- Technology choice and isotope choice are correlated. Complementary, broad program:
  - TeO_2: detect (faint) Cherenkov signal
    - Technology development: US and Europe
    - Pilot measurements: US
  - Scintillating bolometers ($ZnSe$, $ZnMoO_4$, $CdWO_4$)
    - Technology development: Europe and US
    - Pilot measurements: Europe
  - Surface/bulk discrimination
    - Pulse-shape discrimination with superconducting films
    - Scintillating films

US-CUPID R&D Focus

- α/β (or surface/bulk) discrimination
- Improvements in bulk contamination (residual γ background)
- Verification of cosmogenic backgrounds
- Demonstration of scalability
  - ☞ Isotopic enrichment
  - ☞ Crystal production
- Complementary programs in US and Europe

High risk = needed before downselect

Medium risk = important (long lead time)

Institutions

- ANL: TES bilayers
- Berkeley: LD (TES), ^{130}Te enrichment, radio-assay
- MIT: scintillating crystals, LD, simulations
- VT: LD, underground infrastructure
- UCLA: LD
- USC, LLNL: ^{130}Te enrichment
- Yale: muon tagger, surface backgrounds